The Effect of FUV Radiation on C-Shocks: Implications for H_2O and Related Species

in support of Herschel/WISH
and with collaboration of Gary Melnick & Volker Tolls (CfA), Agata Karska (Poland), Michael Turner (SJSU) with funding from NASA/ADAP program

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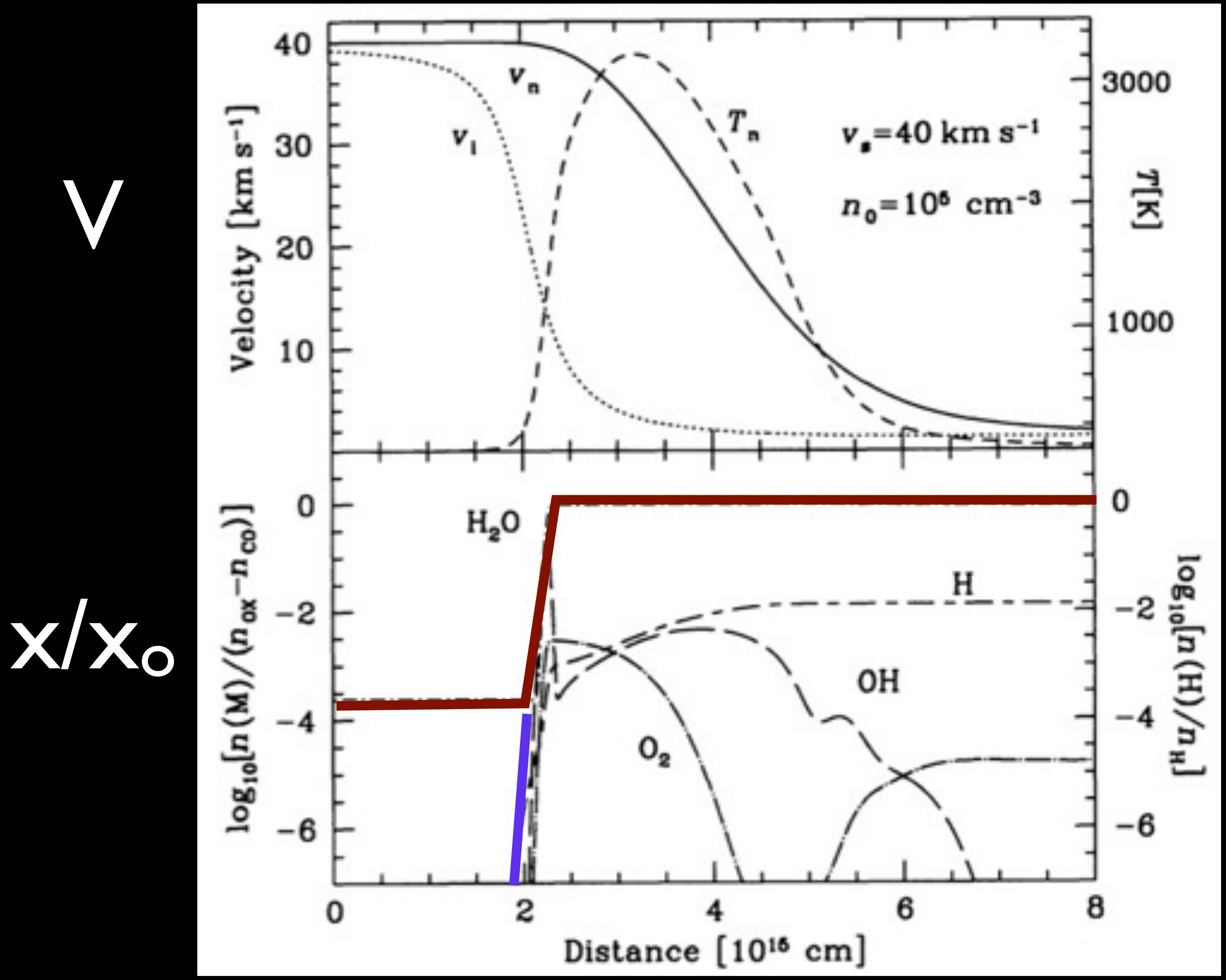
C-Shock Profile



Kaufman & Neufeld 1996; Draine 1983

$H_2 + O \Longrightarrow OH + H$

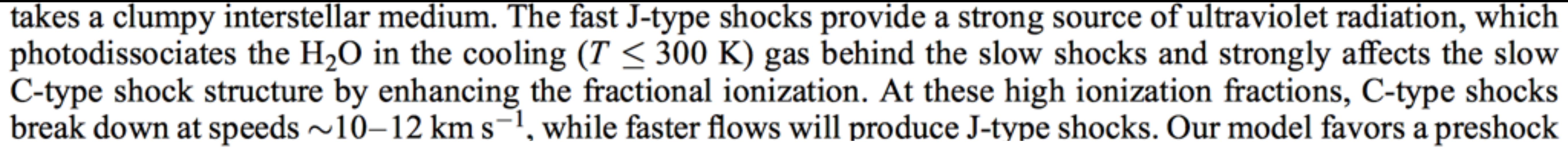
$H_2 + OH \Longrightarrow H_2O + H$

- Continuous T, v
  - Low ionization fraction, carried by ions or grains bound to magnetic field
  - Efficient coolants so that shock doesn't "break down" (below 40 km/s)
- For v ~ 15 km/s, T high enough to gas-phase O ends up converted to water
- For v ~20 km/s, water ice is efficiently sputtered off grains and added to the gas phase

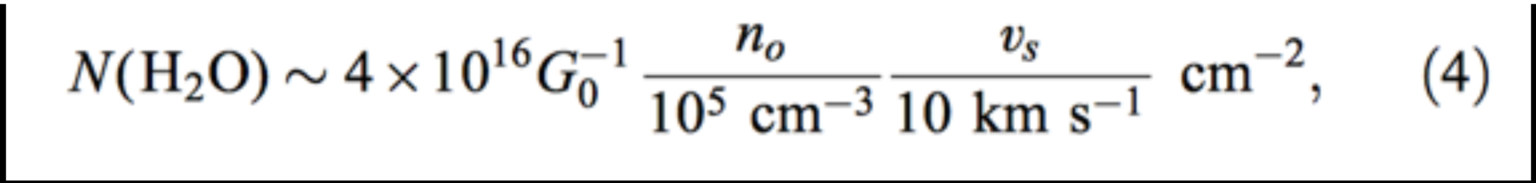
But something is missing…

C-shocks influenced by the environment near SNRs

(Snell et al. 2005)



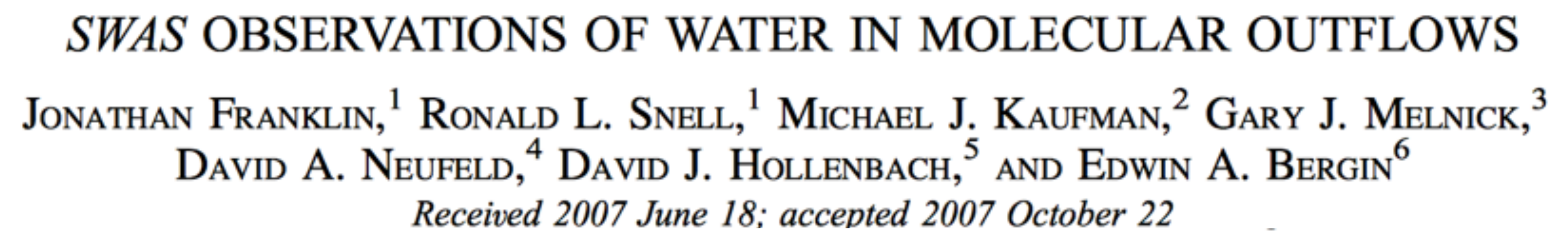
takes a clumpy interstellar medium. The fast J-type shocks provide a strong source of ultraviolet radiation, which photodissociates the H_2O in the cooling ($T \leq 300$ K) gas behind the slow shocks and strongly affects the slow C-type shock structure by enhancing the fractional ionization. At these high ionization fractions, C-type shocks break down at speeds ~10–12 km s^{-1}, while faster flows will produce J-type shocks. Our model favors a preshock



$$N(H_2O) \sim 4 \times 10^{16} G_0^{-1} \frac{n_o}{10^5\ \mathrm{cm}^{-3}} \frac{v_s}{10\ \mathrm{km\ s}^{-1}}\ \mathrm{cm}^{-2}, \qquad (4)$$

Most shocked H_2O is not at an abundance of 10^{-4} in outflows

(Franklin et al. 2007)



SWAS OBSERVATIONS OF WATER IN MOLECULAR OUTFLOWS

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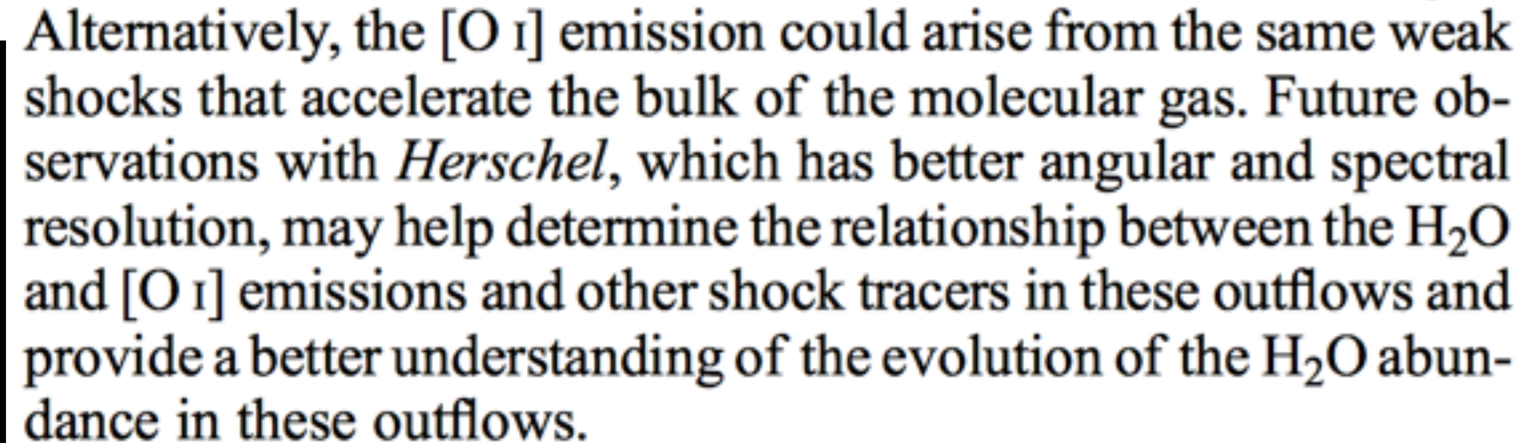
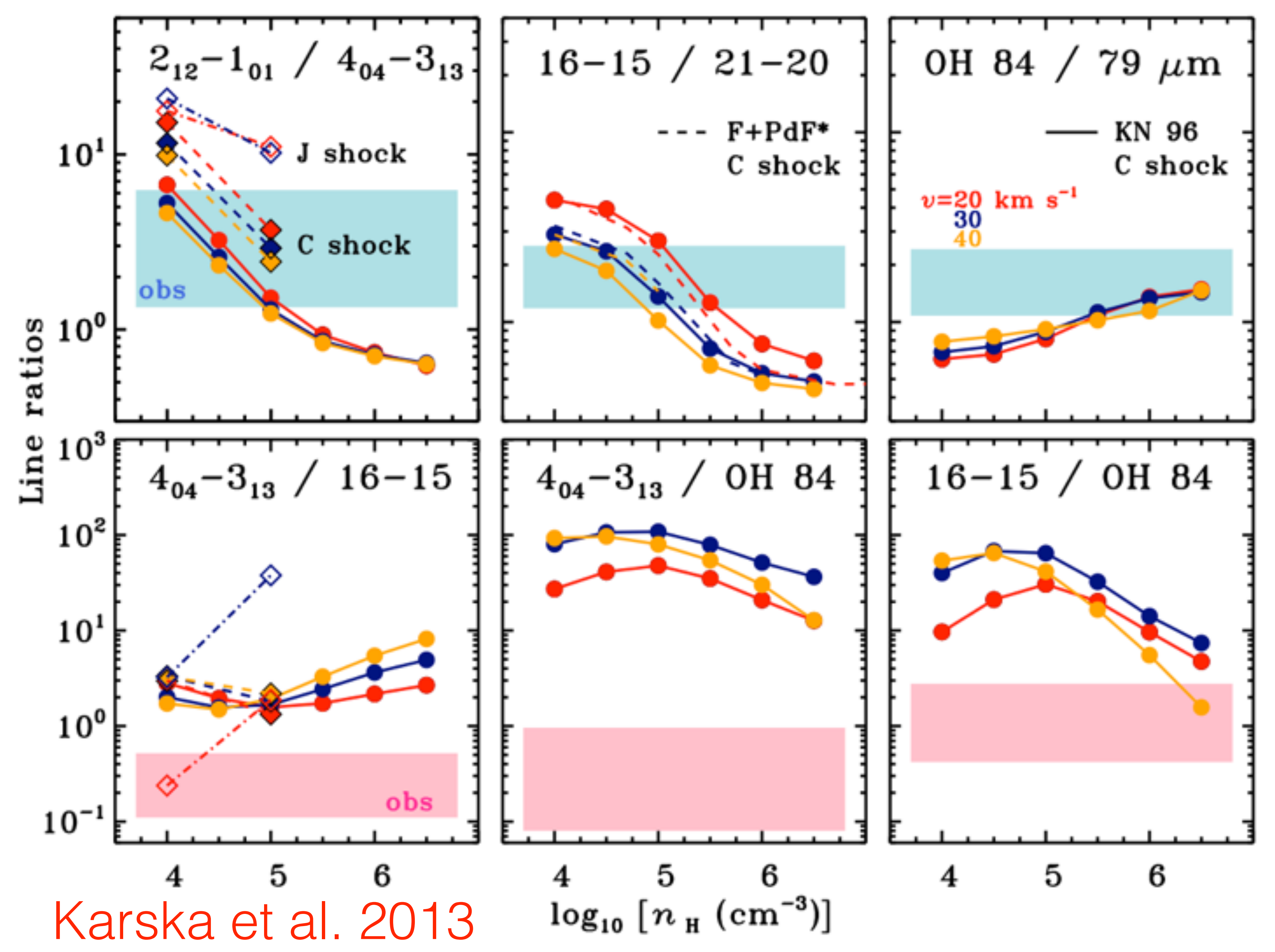


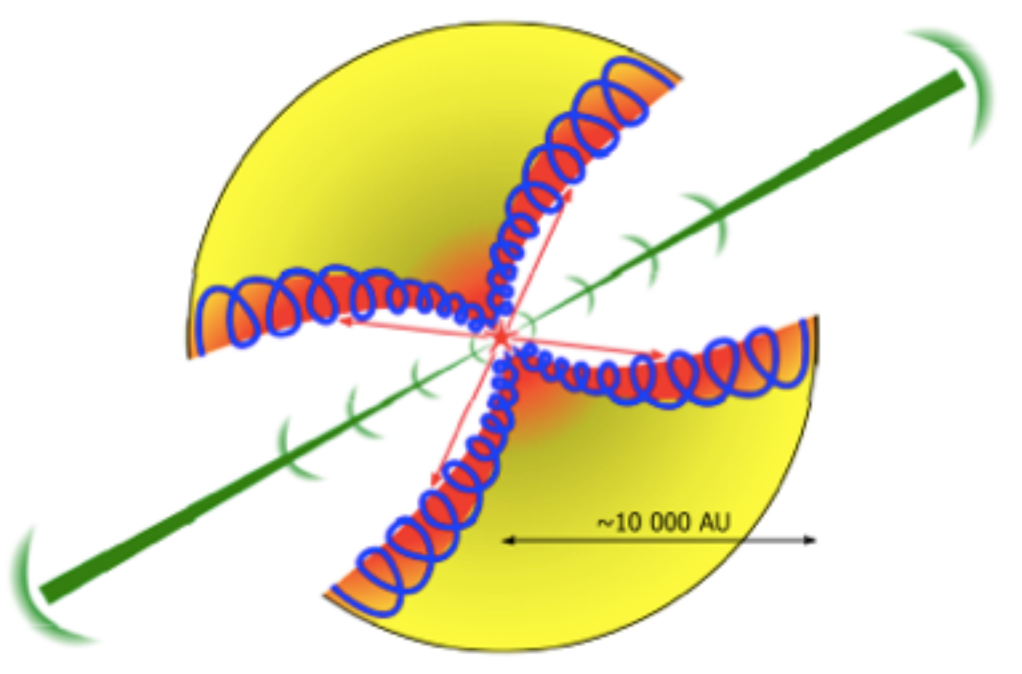
Alternatively, the [O I] emission could arise from the same weak shocks that accelerate the bulk of the molecular gas. Future observations with *Herschel*, which has better angular and spectral resolution, may help determine the relationship between the H_2O and [O I] emissions and other shock tracers in these outflows and provide a better understanding of the evolution of the H_2O abundance in these outflows.

But something is missing…

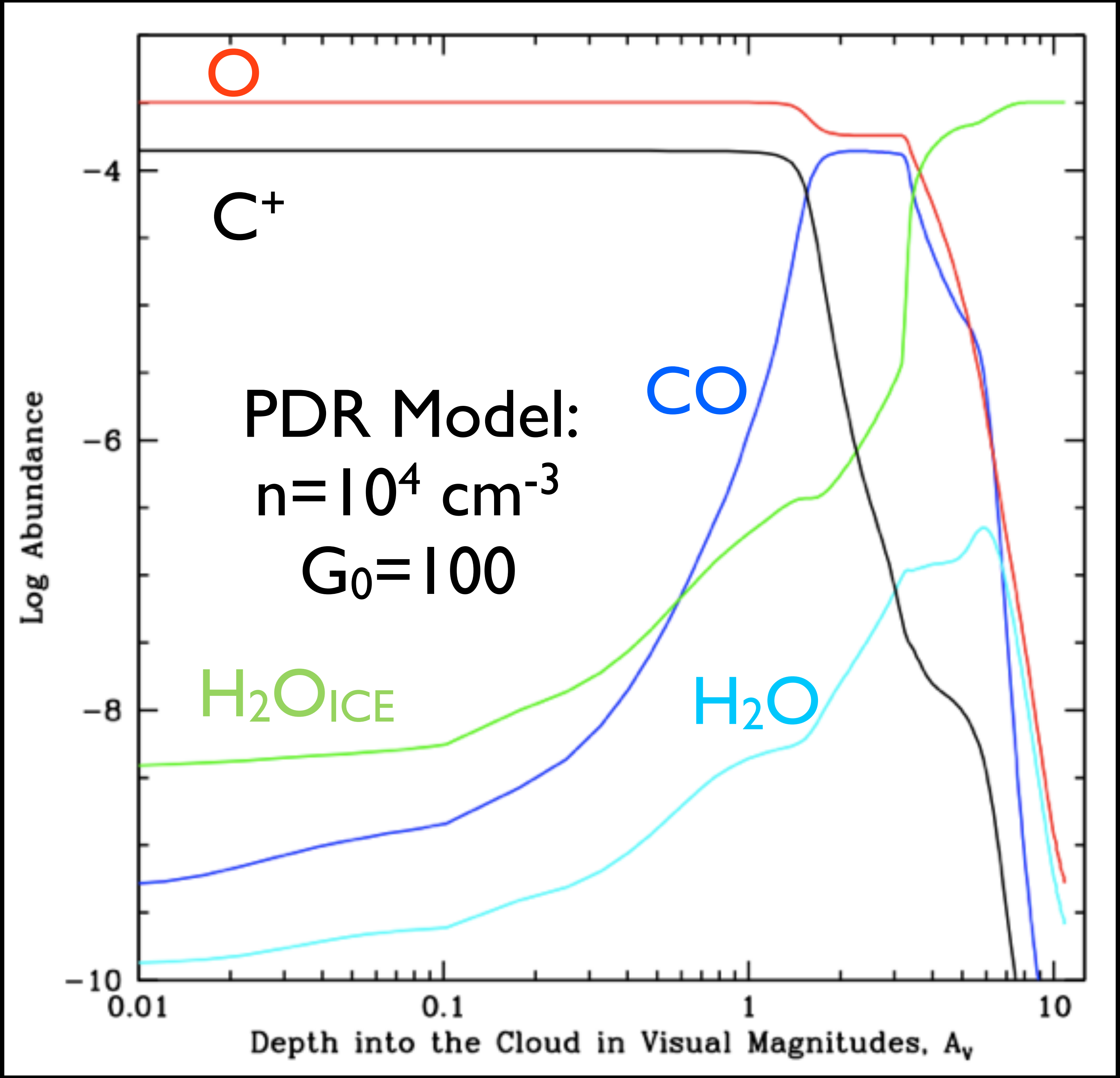


Karska et al. 2013

What are the preshock conditions in the protostellar environment?



Visser et al. 2011



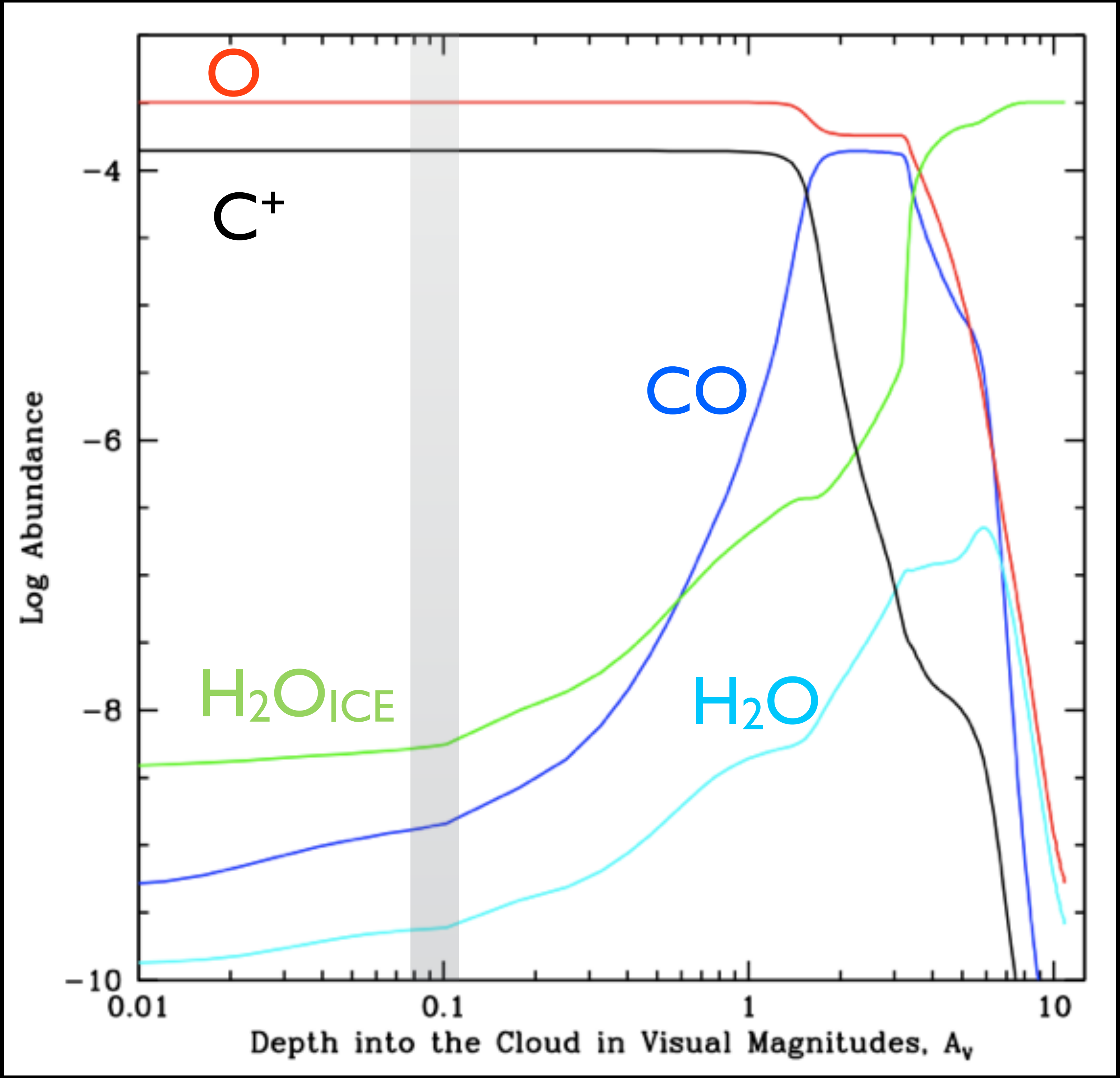
PDR Model:
$n=10^4$ cm^{-3}
$G_0=100$

Hollenbach et al. 2009

What are the preshock conditions in the protostellar environment?

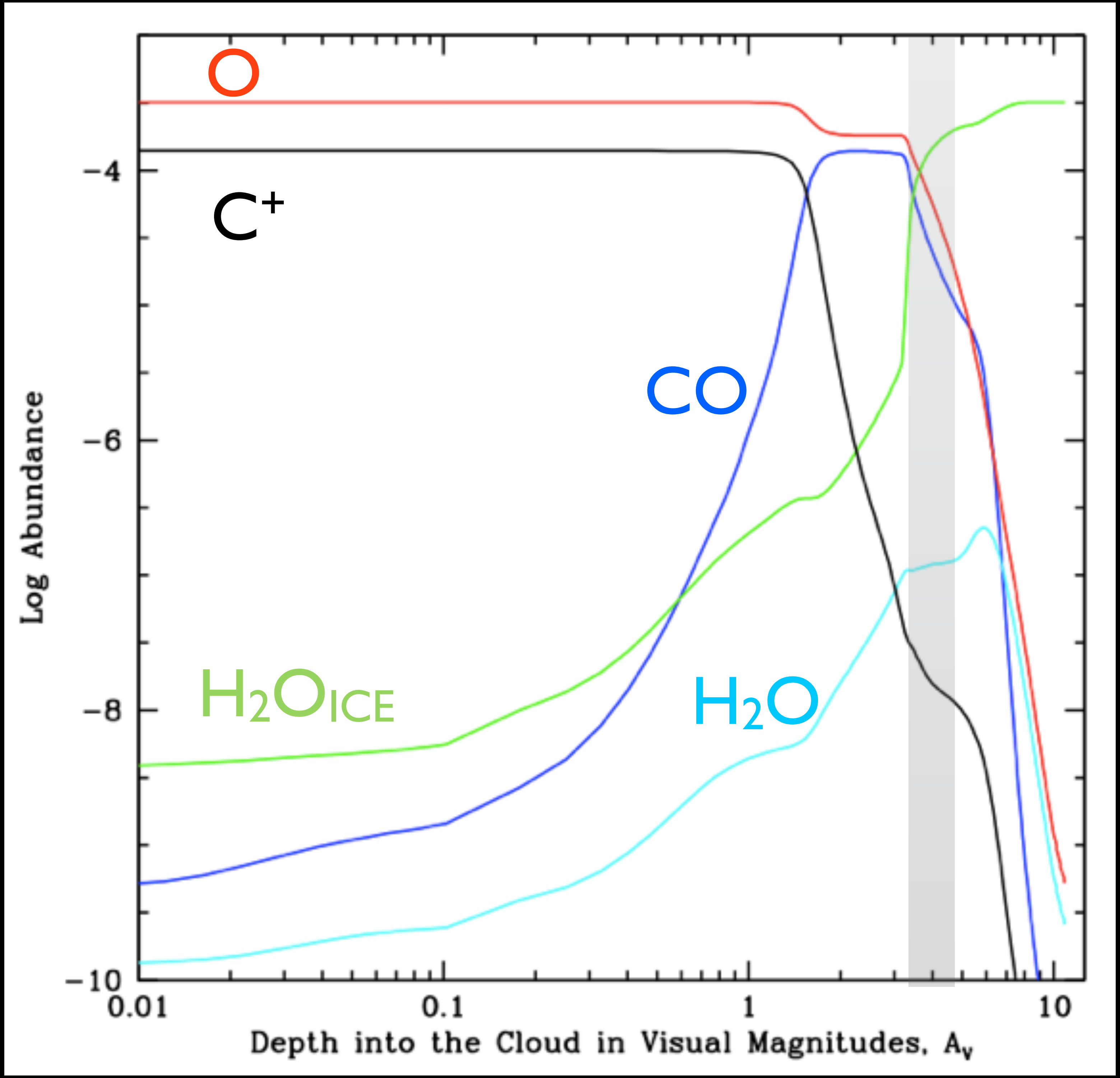
$A_V = 0.1$:
All oxygen available but high ionization fraction makes shocks breakdown

Hollenbach et al. 2009



What are the preshock conditions in the protostellar environment?

A_V = few:
Oxygen frozen out by factor of 10. Ionization may not allow shocks above sputtering speed.

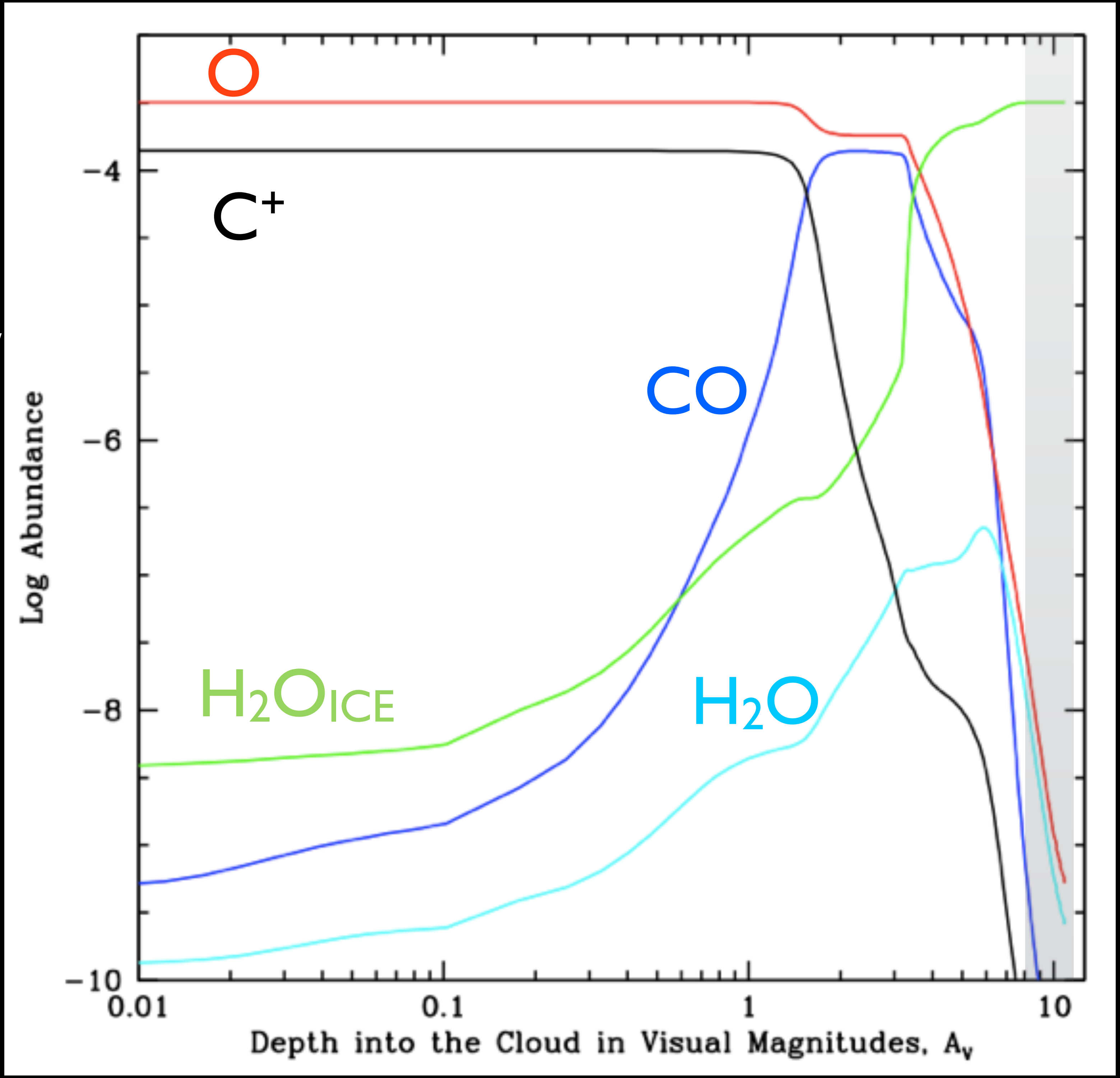


Hollenbach et al. 2009

What are the preshock conditions in the protostellar environment?

$A_V = 10$:

All oxygen frozen out; low water without sputtering since O is locked in the ice.



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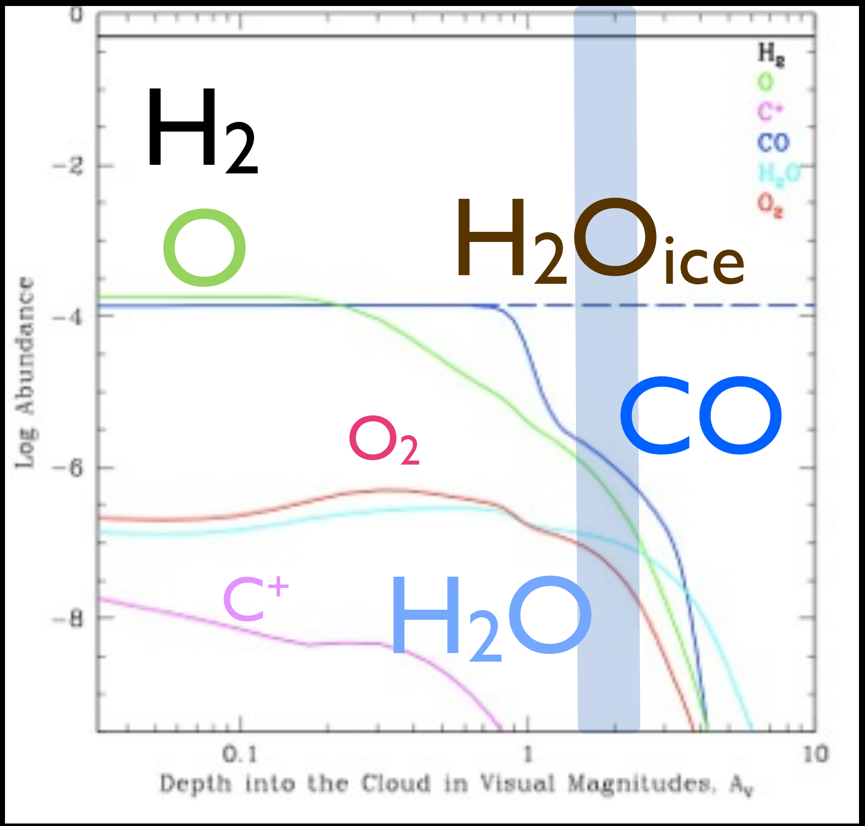
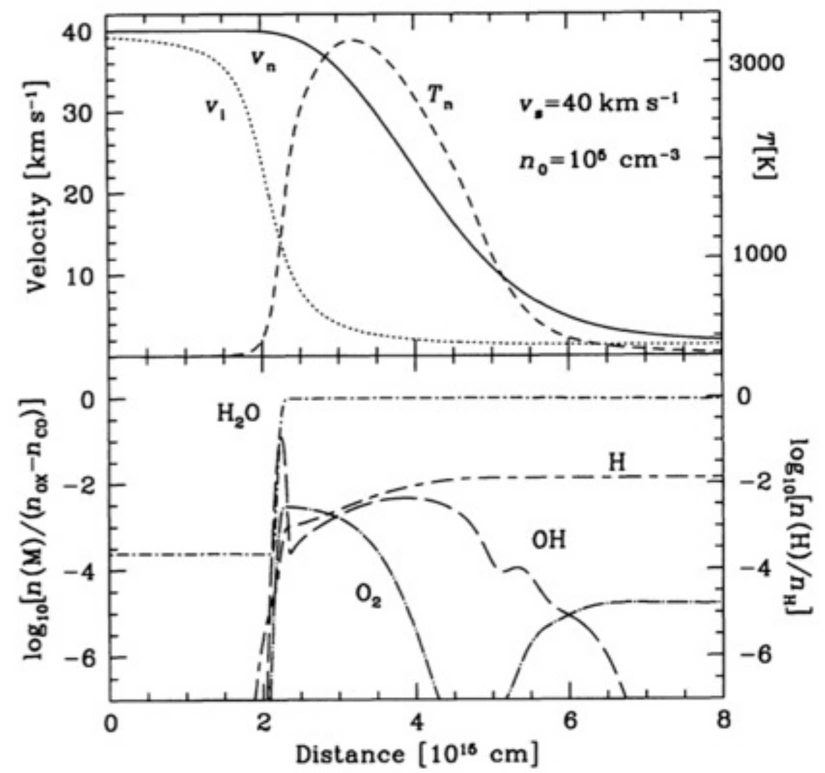


G_0, n, A_V —> L, x

Preshock PDR

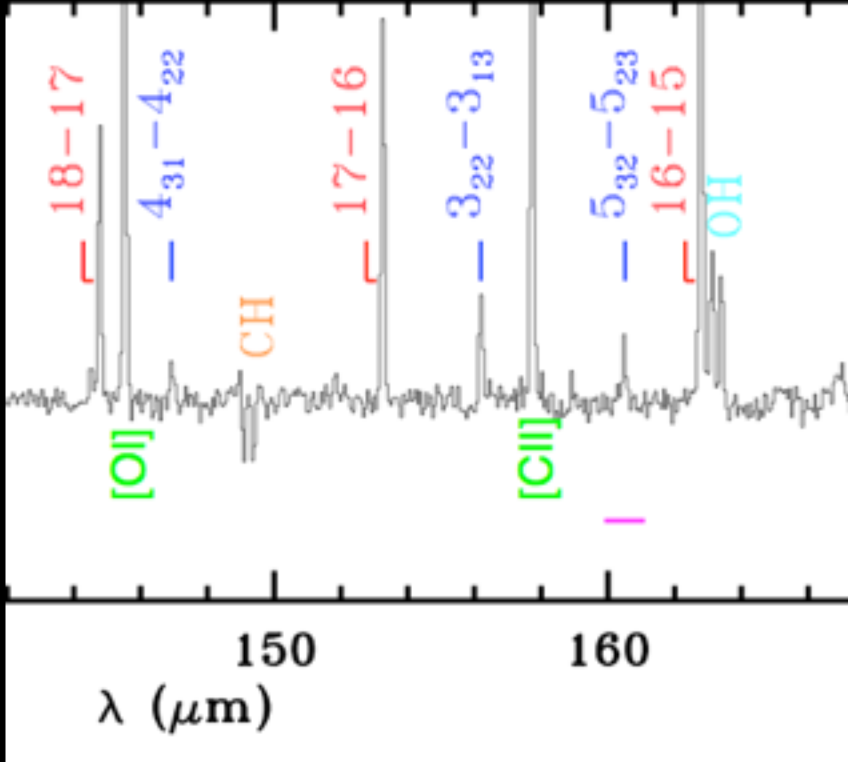
FUV Illuminated Shock Model



Run for v = 5 km/s —> v_{max}

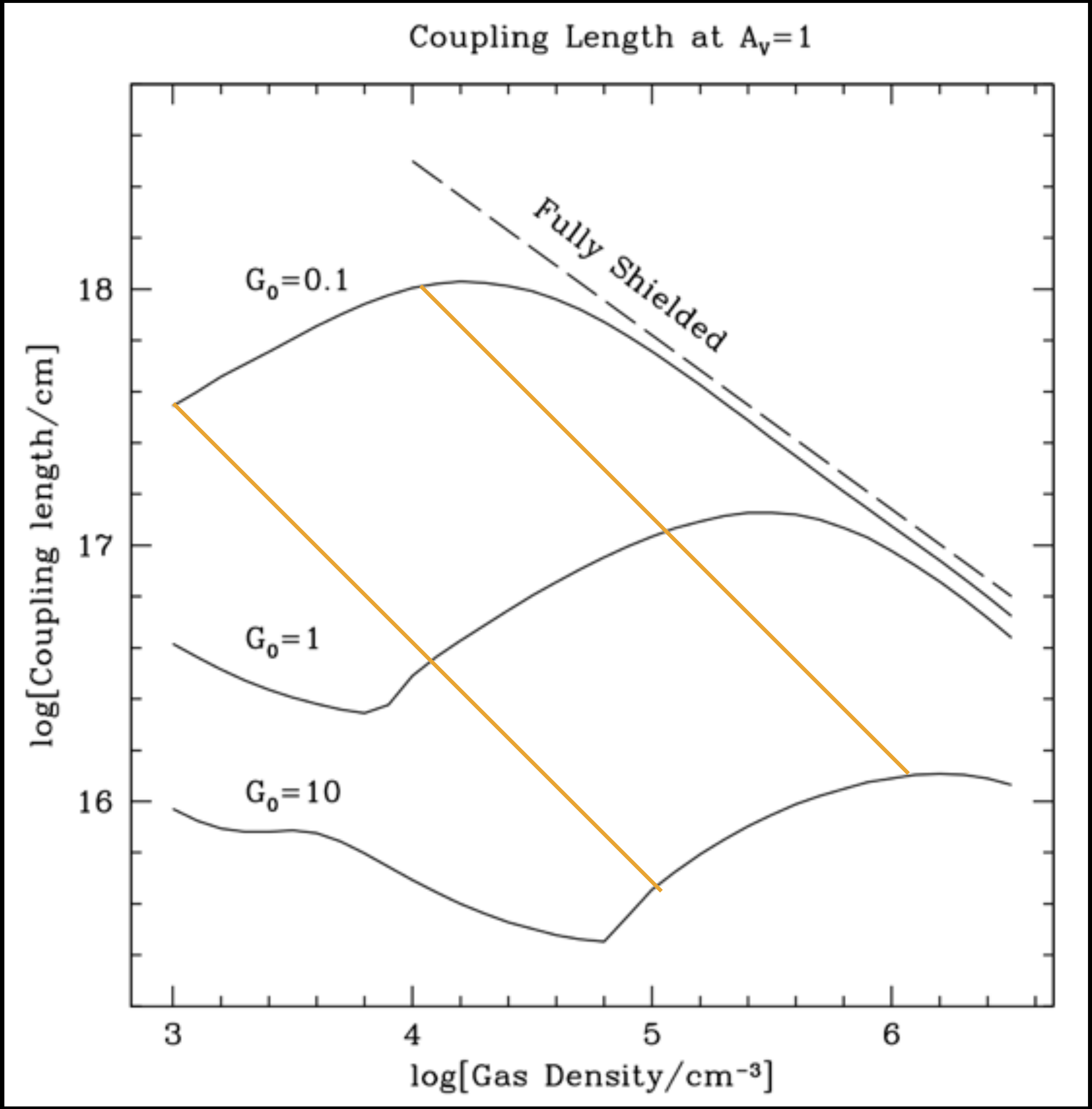
G_0, n

Resulting Spectrum
H_2O, O, OH, CII



Effect of FUV on Shock Length

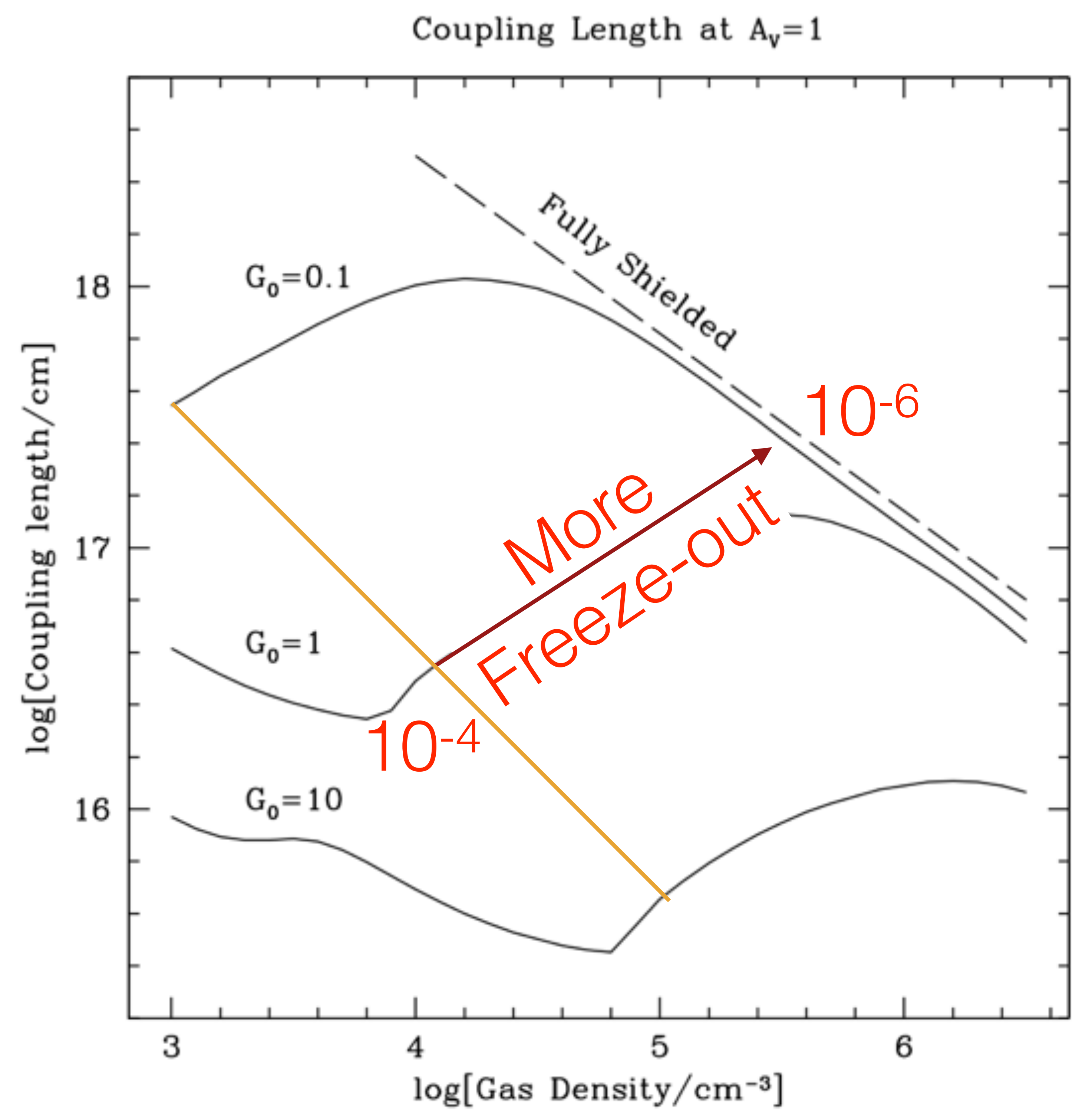
- Length scale controlled by ionization fraction and ionization carriers
- Detailed calculation using PDR model for different A_V, G_0 and pre-shock density
- $L \sim 1/n_i\sigma$



105 PDR Models

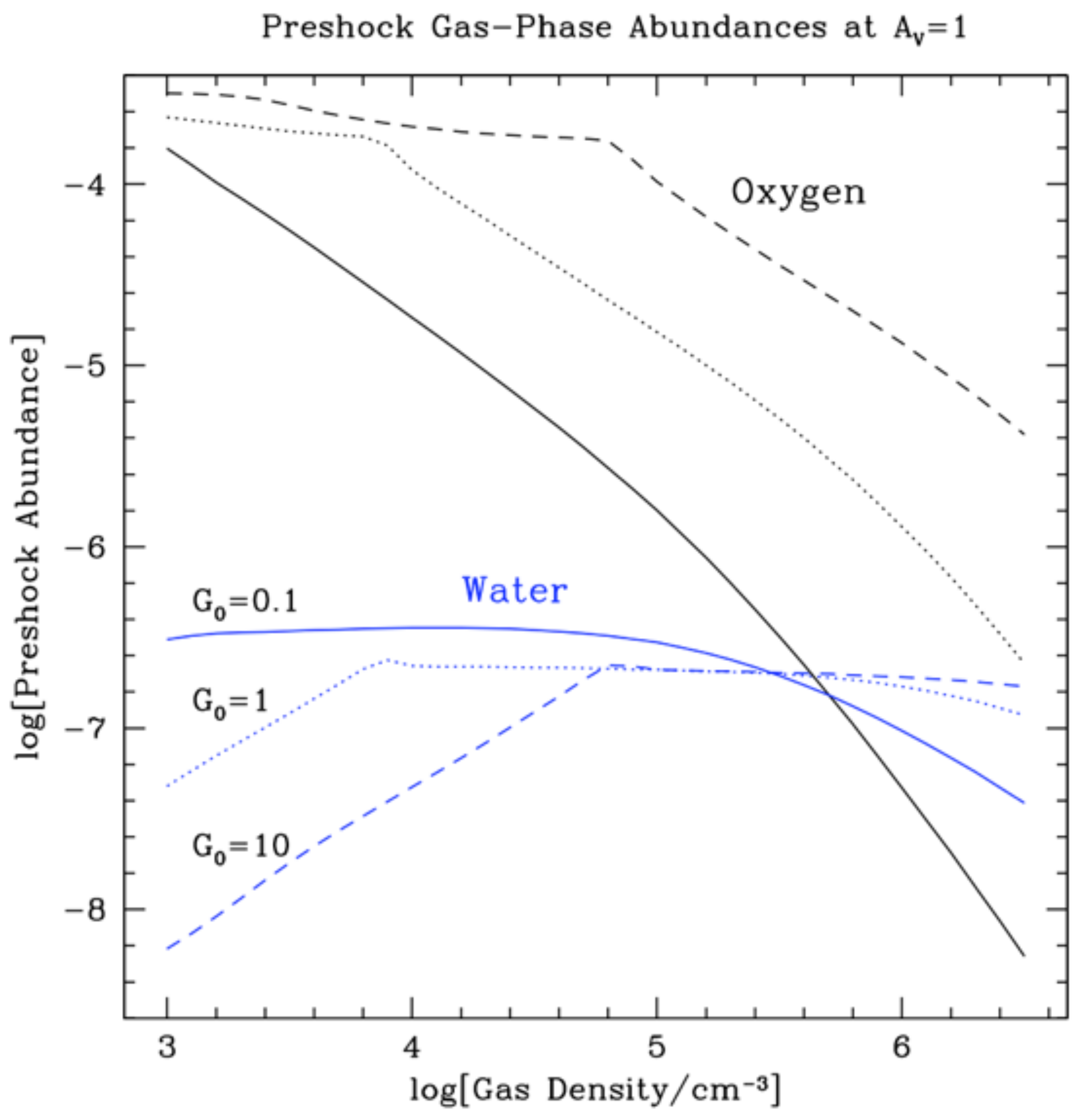
Effect of FUV on Preshock O_{gas}

- Freeze-out controlled by G_0 (desorption) and n (sticking)
- Higher G_0 can drive thermal desorption as well, so scaling relations don't tell everything
- O in the gas ranges from 10^{-4} to 10^{-6}



105 PDR Models

How much oxygen is available to make H_2O in the gas?



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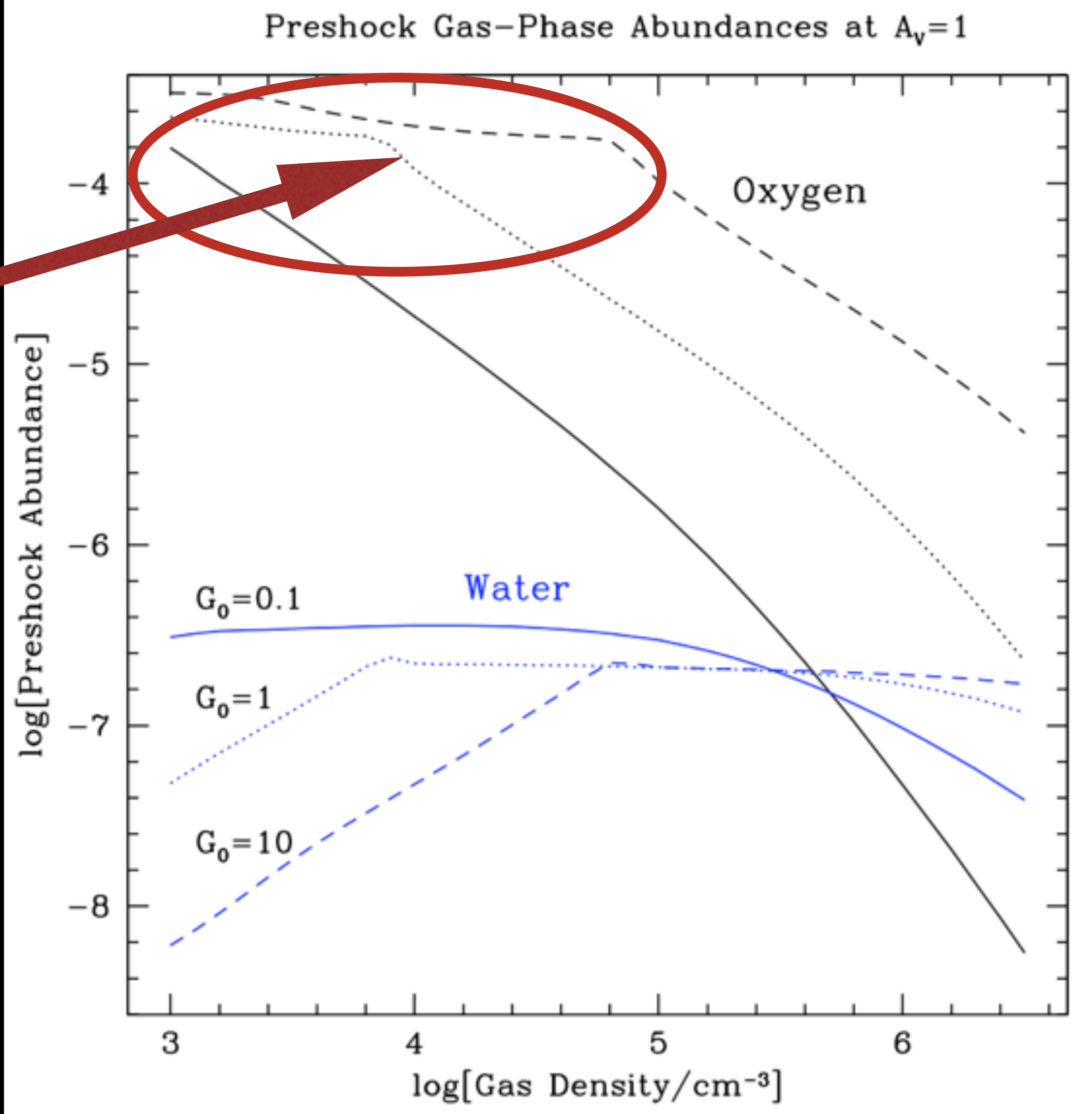
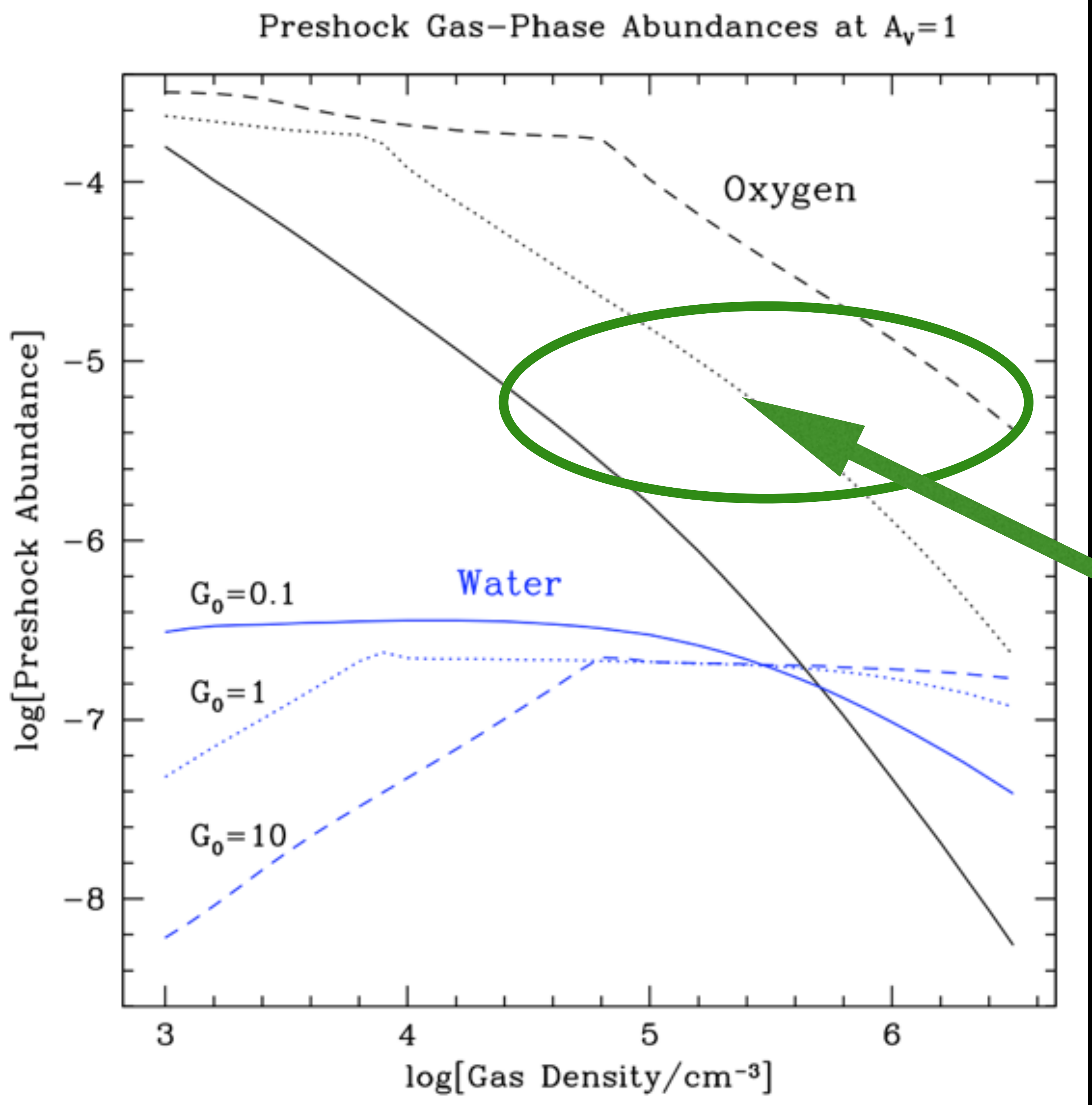


$x_{max}(H_2O)$
$\sim 10^{-4}$

How much oxygen is available to make H_2O in the gas?



$x_{max}(H_2O)$ ~10^{-5} without sputtering

Modeling efforts to date

- Identification of basic process - FUV inherently intertwines shock physics, pre-shock gas-phase abundances, and shock chemistry

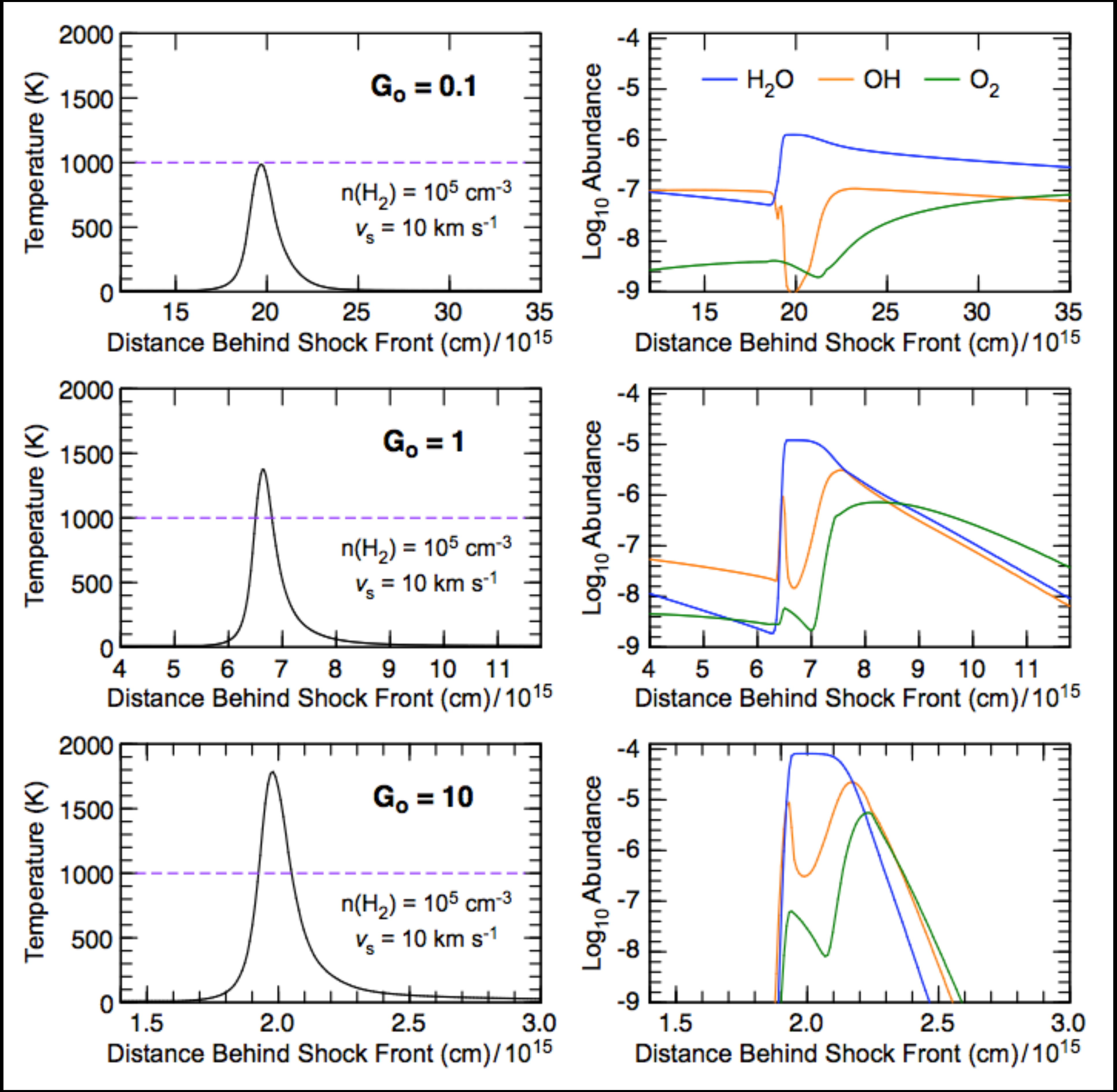
- Search for cases where fine-tuning of the initial conditions allowed for low H_2O abundances

- Now geared up for big parameter study of FUV's effect on O-chemistry

    - O_2 as a test case (Melnick & Kaufman 2015)

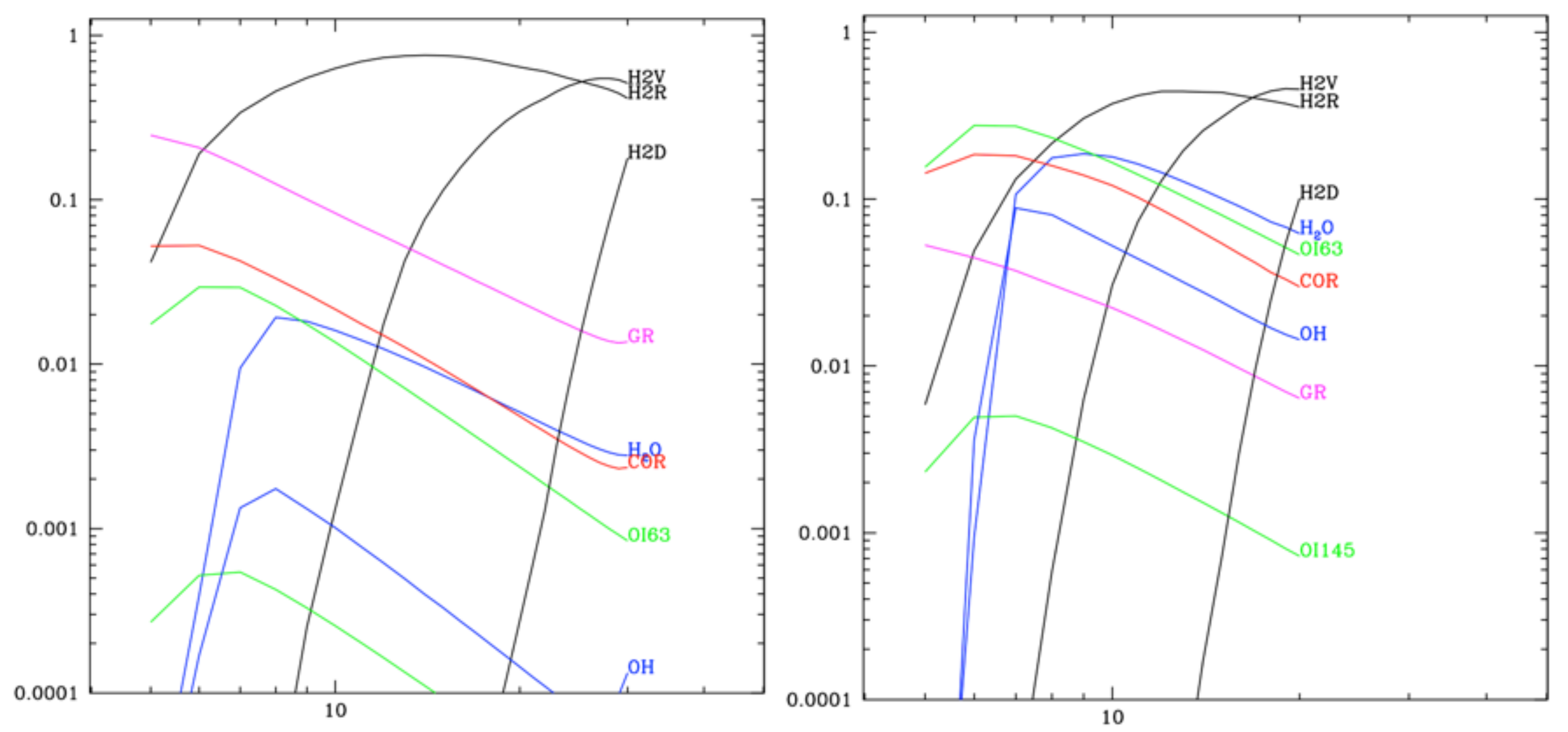
    - Emission from H_2O and related species (OI, CO, OH, etc.)

- As FUV field is increased, length scale goes down/ T_{max} goes up
- As FUV field is increased, available gas-phase oxygen goes up
- As FUV is increased, post-shock gas is more dissociated



$n=10^5$ cm^{-3}

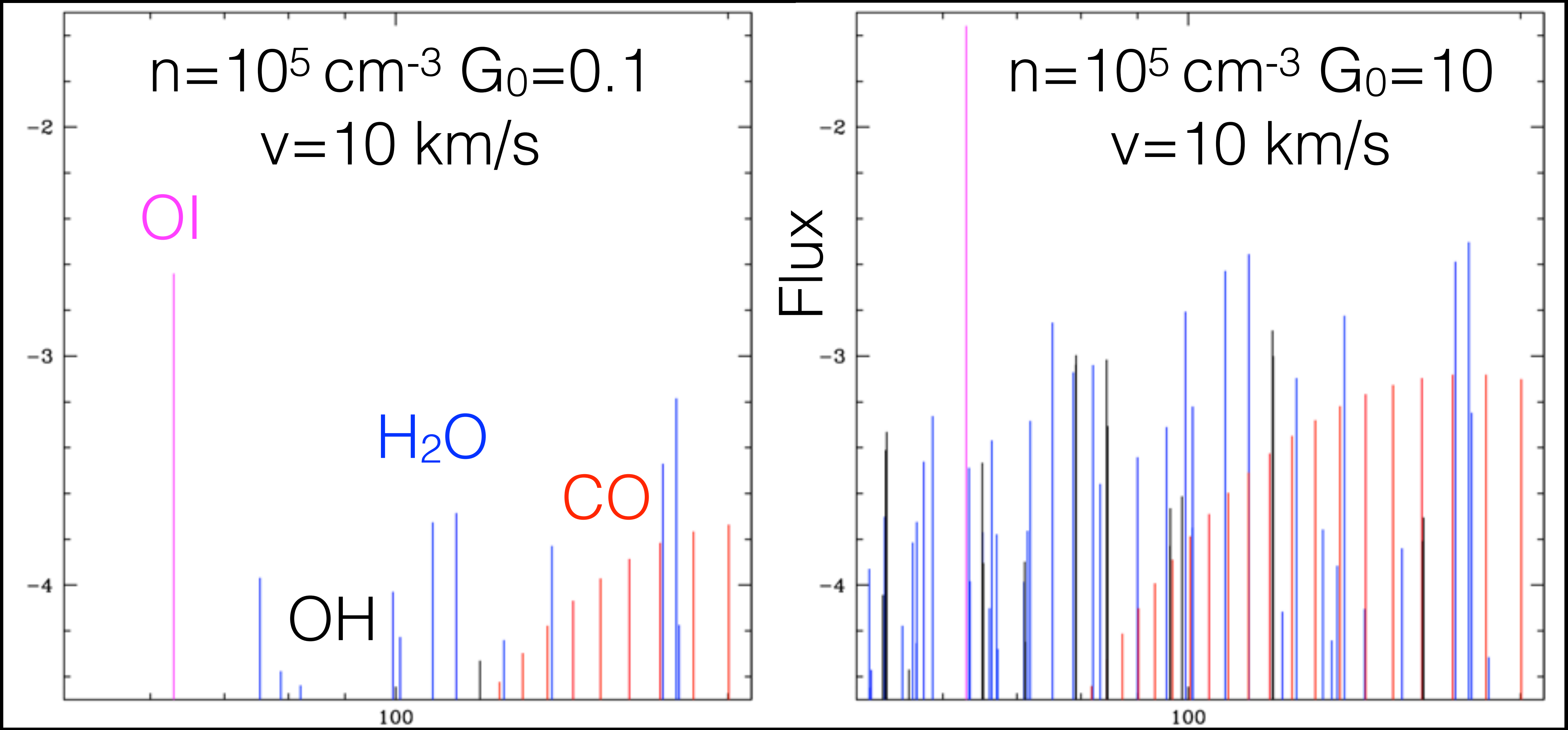
$G_0=0.1$ $G_0=10$



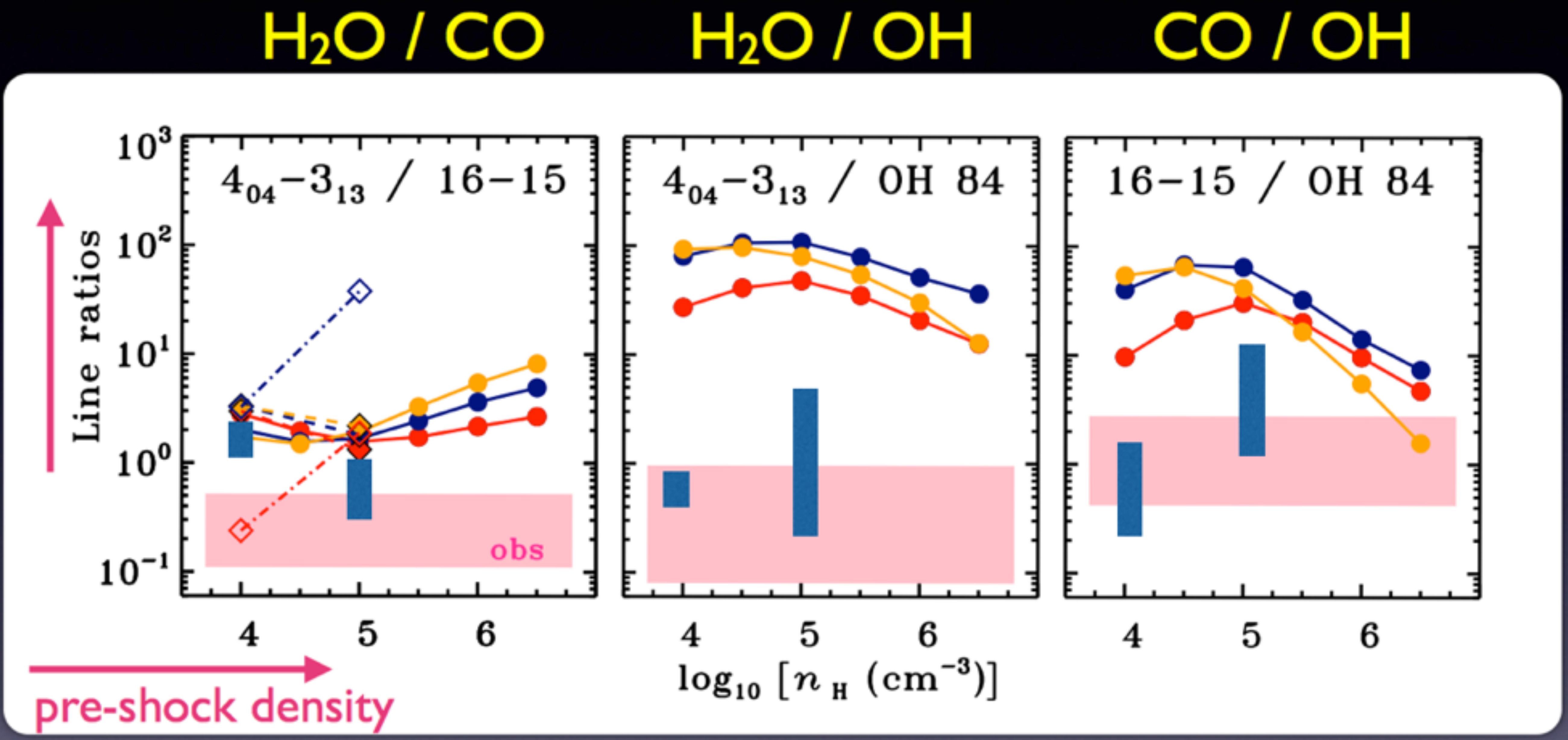
Cooling Fraction

V (km/s)

Spectra for detailed comparsions in progress



FUV moves ratios in the right directions



Karska+14b

FUV C-Shocks: Summary

- Higher G_0/n: More O and H_2O in pre-shock gas
- Higher G_0/n: Smaller velocity at which H_2O formation turns on and lower velocity of C-shock breakdown, perhaps excluding sputtering
- Higher G_0/n: Greater relative O and OH emission from downstream gas
- Preliminary results compare well with observations; Parameter study underway to compare with WISH and other outflow samples